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The Importance of Spatial Effects for Environmental Health Policy and Research

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ABSTRACT

Issues of spatial scale and resolution are intrinsic to efforts aimed at protecting and improving environmental health. Deciding on an appropriate policy or selecting a suitable research design implies a decision, either implicit or explicit, about spatial scale and resolution. This article looks at issues in the context of environmental health, reviews crucial problems and questions, and examines examples of spatial effects on analytical results related to causal inference, disease clustering, and analysis and interpretation of census data. The discussion focuses on the need to consider spatial issues as a key component of informed, well- reasoned decisions about safeguarding environmental health.

Key Words: environmental health, modifiable areal unit problem, spatial scale, spatial resolution, spatial boundary, geographic scale, environmental health policy, environmental health research.

INTRODUCTION

Effective and efficient protection of human health from the adverse effects of environmental pollution necessarily involves consideration of geographical location and related issues of spatial scale. The importance of spatial scale for designing efficacious intervention strategies and research projects is a well-recognized but often under appreciated precept in environmental health. Today, this precept is gaining new prominence because of recent advances in computer technology and related software that allow for rapid processing, merging and displaying geographically referenced data. The relative ease of using Geographical Information Systems (GIS) to link and display maps of pollution sources, residential location, and morbidity and mortality has led to greater reliance on them as a decision-making

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tool. It is becoming increasingly important, therefore, to understand the key spatial issues that affect the capability of GIS to improve environmental health studies, make risk assessments more realistic, and inform environmental health policies.

This article provides a brief overview of the need to consider spatial scale (extent of the area examined) and resolution (level of data aggregation) in the development and evaluation of effective environmental health policy. The emphasis is on identifying issues of spatial scale and resolution that must be addressed explicitly so that GIS approaches can successfully foster improved decisions about environmental health. The subsequent sections are structured, first, to put spatial issues in the context of environmental health, second, to identify important problems related to spatial scale and resolution, third, to examine selected examples of ways that spatial scale and resolution can affect analytical results and, fourth, to summarize the importance of spatial scale and resolution for environmental health research and policy.

SPATIAL SCALE IN THE CONTEXT OF ENVIRONMENTAL HEALTH

The field of environmental health is generally concerned with understanding and managing (a) the effects of people on the environment and (b) the effects of the environment on people. Our focus here is on the latter case, and specifically on the effects of biological, chemical or physical environmental agents on human morbidity and mortality. Typically, research to better understand environmental health problems and policies to prevent or reduce environmental health risks are predicated on an established or postulated chain of events, which is sometimes referred to as the environmental health paradigm (Sexton *et al.* 1995a,b).

As shown schematically in Figure 1, the environmental health paradigm can be conceptualized as a series of steps intervening between release of toxic agents into the environment and agent-related harm in people. (1) A pollution source(s) is present. (2) Pollutants are released to the environment. (3) Concentrations of pollutants occur in environmental media, as, for example, in air, dust, food, soil or water. (4) Contact occurs between humans and pollutants in environmental media. (5) Pollutants are absorbed into the human body and they or their metabolites reach a site of toxic action. (6) The result is pollutant-related disease, disability, dysfunction, or death. Included in the paradigm are important mechanisms (determinants), defined as fundamental processes or factors that determine exposure, dose or adverse consequences in human populations. Mechanisms may be biological (*e.g.*, movement of lead across the blood-brain barrier), chemical (*e.g.*, interactions with sulfydryl groups), physical (*e.g.*, lead in plumbing leaching into drinking water) or sociological (*e.g.*, lifestyle attributes that affect consumption of tap water). Although they are diverse, mechanisms share common functional properties: they control, determine, or regulate key processes or events.

The environmental health paradigm portrayed in Figure 1 is obviously a simplified conceptual construct, and is not meant to capture the full range of dynamic complexity inherent in environmentally related illness and injury. In actuality, for most hazardous environmental agents available scientific knowledge is inadequate to elucidate and quantify all of the relevant steps and mechanisms in the paradigm with an acceptable degree of certainty. As summarized in Table 1, attempts to

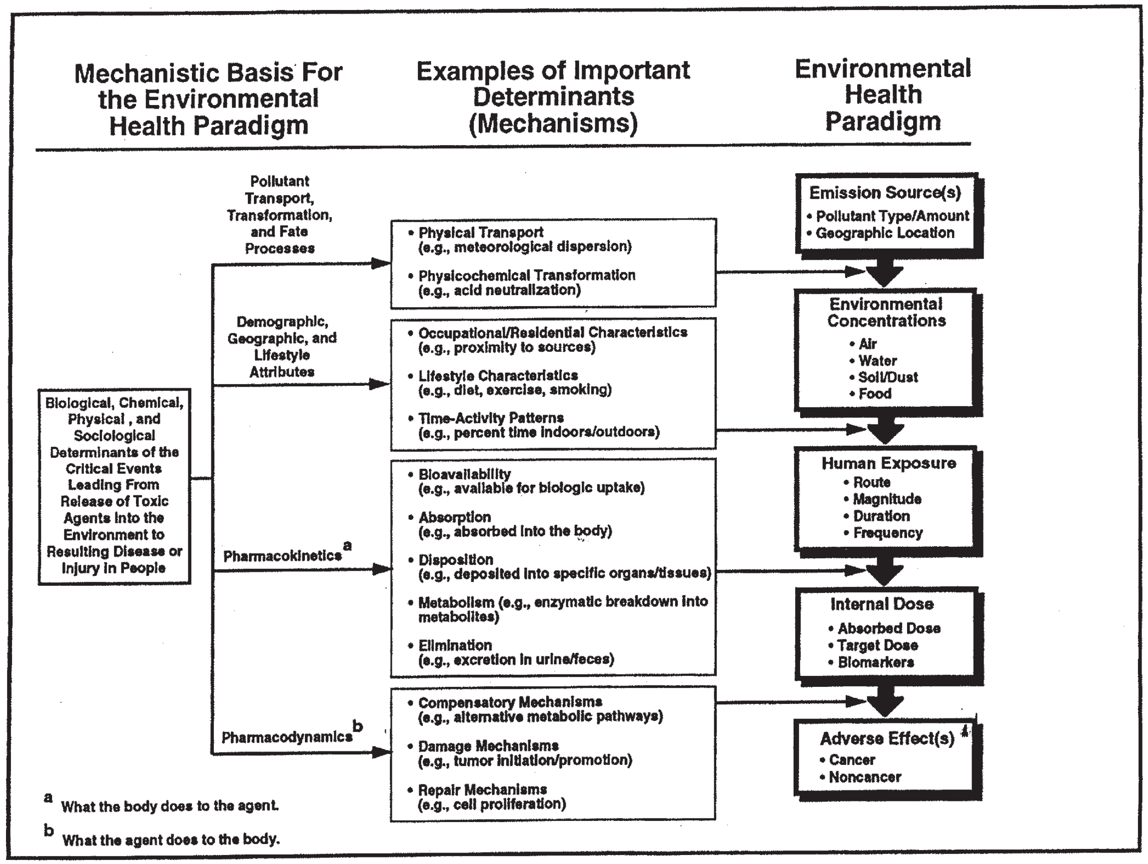

Figure 1. The Environmental Health Paradigm — key steps and mechanisms intervening between release of toxic agents into the environment and agent-related harm in people (from Sexton *et al.* 1995a,b).

Table 1. Common problems that complicate attempts to establish causality between exposure to environmental agents and related adverse health effects (from Sexton 1997).

1.	Incomplete understanding of disease etiology
2.	Wide range of non-environmental causes for most diseases to which environmental agents contribute
3.	Environmental agents often enhance or exacerbate, rather than cause disease or dysfunction
4.	Paucity of methods, measurements, and models to (a) estimate exposure, dose, and effects accurately, and (b) characterize variability across individuals, subpopulations, time, and space accurately
5.	Scarcity of surveillance and reporting systems for exposure and environmentally related health outcomes (*e.g.*, limited information about incidence and prevalence)
6.	Long latency period from exposure to adverse health effects for many environmentally induced diseases (*e.g.*, mesothelioma)
7.	People experience multiple exposures, both simultaneously and sequentially, to a diversity of environmental agents
8.	Observed health endpoint (*e.g.*, lung damage) may not be the primary target system (*e.g.*, immune system)
9.	Inherent variability among individuals and population subgroups in biological susceptibility to environmentally induced illness and injury

establish causality between human exposure to environmental agents and subsequent adverse health effects are complicated by a diversity of recurring problems (Sexton 1997). In addition to the intrinsic complexity and uncertainty of demonstrating a link between exposure and effect, there are temporal and spatial variations in the mechanisms and events that comprise the environmental health paradigm.

Much of the emphasis in environmental health is on understanding the complicated process by which pollutant exposures cause adverse human health effects and intervening where and when appropriate to prevent or reduce related illness and injury. Consequently, most environmental health research studies and intervention strategies converge around three fundamental variables: (1) exposure — human contact with environmental agents; (2) effect — prevalence (or incidence) of human health consequences likely to be caused or exacerbated by exposure to environmental agents; and (3) exposure-effect link — human vulnerability to the effects of exposure, especially variability in biological susceptibility within and between individuals as well as within and between population subgroups (Sexton 1997).

The critical point for our purposes here is the fact that all three exhibit significant geographical variability. That is to say, the true distribution of environmental exposures, human health effects, and the link between exposure and effect (susceptibility) varies depending on the geographic location, the spatial scale used for analysis, and the spatial resolution of the aggregated data. It is, therefore, axiomatic that consideration of spatial scale and resolution is an important aspect of environmental health.

PROBLEMS RELATED TO SPATIAL SCALE AND RESOLUTION

Traditional public health disciplines, such as epidemiology, exposure analysis and biostatistics, have long recognized the need to address spatial issues. For example, exposure analysts routinely confront the spatial realities of uneven geographic distributions of people and pollution, and direct significant resources toward measuring or estimating exposure in ways that will minimize misclassification errors. Biostatisticians understand that spatial scale and resolution affect most, if not all, statistical analyses of exposure-effect relationships, and are concerned with problems related to misaligned data, data incompatibility, and validity of inferences. Epidemiologists are cognizant that spatial scale and resolution have important implications for designing and interpreting studies, and are trained to avoid the "ecological fallacy" of drawing inferences about underlying exposure-effect relationships in individuals from aggregate data in populations.

Recently, because of the expanding use of GIS as a decision tool, geographers have begun to apply spatial technologies and modes of analyses to environmental health issues. This has focused attention on a variety of problems confronting researchers and policy makers, including questions about geographical scale, data resolution, spatial boundaries, and the modifiable areal unit problem.

Geographic (Spatial) Scale

Scale in a geographical context refers to the spatial (or areal) extent of a given analysis. The range of geographical scales typically applied to environmental health issues spans the gamut from personal exposure studies, where the emphasis is on pollutant concentrations within a few centimeters of the body (*e.g.*, airborne benzene concentrations in the breathing zone of children), to studies of global health effects (*e.g.*, increased incidence of skin cancer for the world's population due to stratospheric ozone depletion and related increases in UV radiation). Thus, as shown in Figure 2, environmental health issues involve a range of geographical scales spanning five orders of magnitude, from 10^{-1} to more than 10^4 kilometers. It is important to note that these spatial scales, with the exception of a continent or the Earth, are "socially constructed" and therefore not defined in a completely objective manner.

Spatial Resolution

Although the terms scale and resolution are often confused, it is necessary to understand the distinction. Scale refers to the spatial (or areal) extent of the analysis, while resolution identifies the level of aggregation for statistical data gathering. For instance, U.S. census data are collected at several different levels of aggregation, including: block; block-group; tract, Minor Civil Division (MCD);

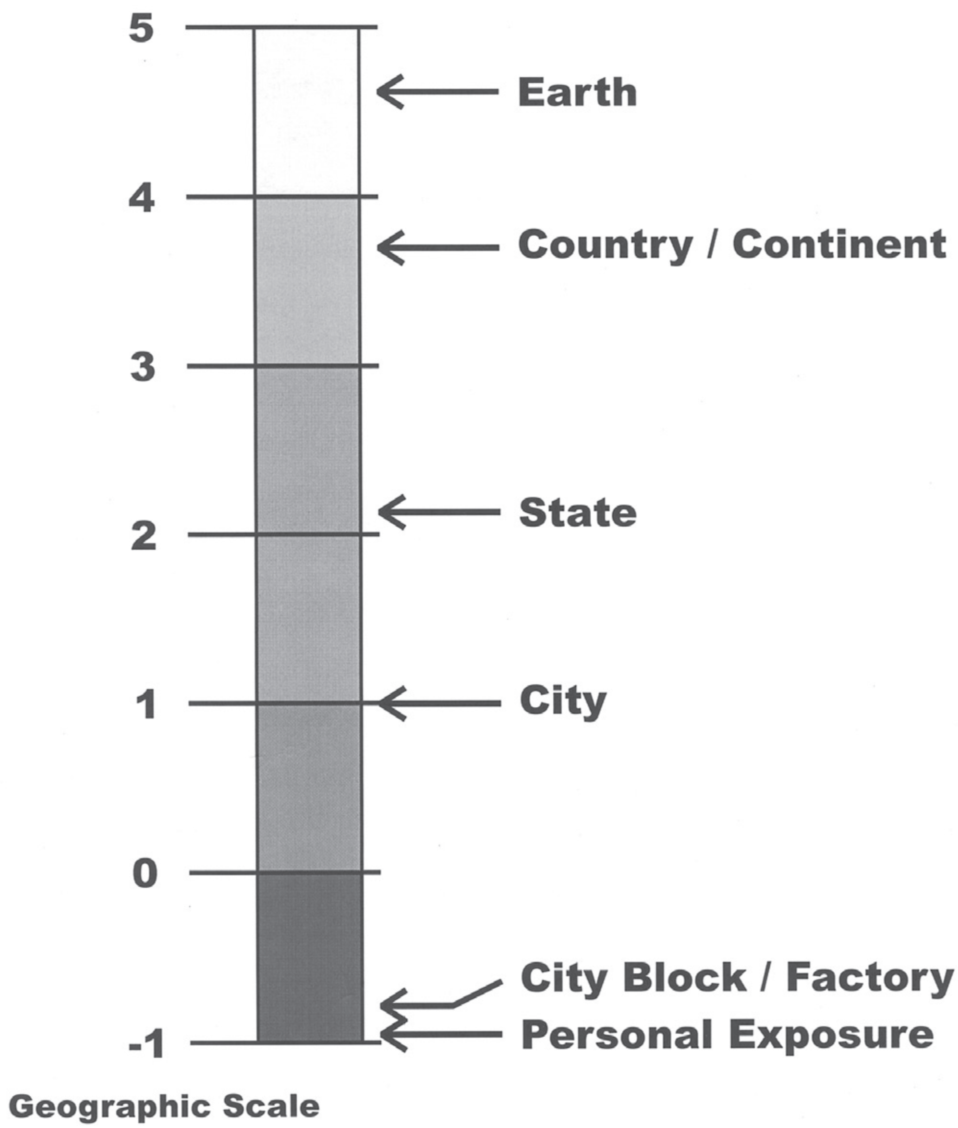

Figure 2. Range of spatial scales involved in environmental health policy and research.

county; state; and region. Typically, these are the levels of resolution for sociodemographic data used in most environmental health studies. In addition, specific address-matched (or point-level) data from institutions such as schools and day care centers may also be available. An important consideration is the fact that not all data gathered by the U.S. Census are collected at all levels of resolution. For example, information about race, age and other basic demographic variables are available at the block level, but detailed data on poverty, housing condition, and employment status are available only at the block-group and tract levels. It is likely, therefore, that results from a study of a particular metropolitan area (geographic scale) using sociodemographic data aggregated at the block level (spatial resolution) will differ significantly from those obtained at the regional geographic scale using tract-level resolution. Thus, there is strong justification for devoting substantial effort to defining optimal spatial scales and levels of spatial resolution for particular kinds of environmental health studies.

Spatial Boundaries

The boundary circumscribing the geographical area of analysis can have important ramifications for results from spatial analysis. In an urban-scale study, for example, the city limits are typically used as the boundary for the unit of analysis. If, however, the analysis were extended several block-groups or tracts beyond this artificial and somewhat arbitrary boundary, then additional pollution sources or different groups of people might be included in study. This could significantly alter results because of differences across political boundaries related to historical industrial development, taxation or zoning ordinances.

Modifiable Areal Unit Problem (MAUP)

All of these types of spatial issues are related to a generally recognized problem, which geographers call the modifiable areal unit problem, or MAUP. The MAUP is a statement of the fact that results from a statistical analysis virtually always depend on the spatial (geographical) scale of the analysis (Openshaw 1984). This suggests that a variable that is significant in a regression analysis at one geographical scale may be insignificant at another, or that point patterns that appear random at one geographical scale may appear clustered at another.

EXAMPLES OF SPATIAL EFFECTS ON ANALYTICAL RESULTS

With this set of problem descriptions as a backdrop, we now examine three examples of the potential implications of spatial scale and resolution for analytical results in environmental health.

Relationship between Spatial Scale and Causal Inference

Etiologic epidemiology studies try to estimate the effect of an environmental exposure on disease risk for a particular target population over a specified period of time. The target population is the group of people about whom we wish to make inferences regarding the causal effect of an exposure. These causal inferences should be based on a causal parameter that compares potential health outcomes in the target population under two different exposure scenarios for the time period of interest. The outcomes are termed "potential" because there may be many of them and no more than one can actually be observed. Those that cannot be observed are termed "counterfactual" because, counter to fact, we cannot observe them. After all, a particular target population cannot experience more than one exposure scenario at the same time.

A causal incidence proportion ratio (IPR) is a causal parameter that compares the incidence proportion (risk) of disease that a target population would experience during a specified time period under two different exposure scenarios. For example, the IPR might be used to compare the risk of disease between exposure scenario 1, where everyone is exposed to pollutant concentration E_1, and exposure scenario 2, where everyone is exposed to pollutant concentration E_2. The IPR is interpreted as the proportionate increase in average risk for members of the target population over the course of the study period that is caused by the difference between exposures E_1 and E_2 (Greenland and Robins 1986; Greenland 1987; Greenland *et al.* 1999; Rothman and Greenland 1998). Theoretically, the value of a causal parameter is the "true" value for the causal effect of an exposure. It is this unobservable value that epidemiologic studies attempt to estimate.

For purposes of illustration, consider a hypothetical town of four people (target population), all of whom are exposed to an environmental pollutant. Two residents live north of a river dividing the town and two live to its south. Figure 3 shows both (a) the disease outcomes actually experienced by people in the town during the study period and (b) potential disease outcomes that would have occurred if no one were exposed. The important point is that IPR values depend on spatial scale. For the two people north of the river, the risk of disease is 1 (2/2) if exposed and 0.5 ($^1/_2$) if not exposed, which makes the IPR equal to 2 (1/0.5). In contrast, for the two people south of the river, the risk of disease if exposed is 0.5 ($^1/_2$) and 0.5 ($^1/_2$) if not exposed, which makes the IPR equal to 1 (0.5/0.5). When we consider the entire town of four people, the IPR is 1.5 (0.75/0.5) based on a 0.75 (3/4) risk of disease if exposed and 0.5 (2/4) risk if not exposed.

In reality, of course, the people in the town (target population) cannot be exposed and unexposed to the environmental contaminant at the same time, so it is impossible to actually observe the IPR values computed above. Nevertheless, the ultimate goal of an etiologic epidemiology study should be to estimate these "true" values as accurately as possible. Our example illustrates that the value of the IPR changes with spatial scale: the IPR equals 2 in the north; 1 in the south; and 1.5 for the entire town. Because the value of a causal IPR can change as the composition (*e.g.*, susceptibility) of the target population changes, and because the composition of the target population varies with spatial scale, the "true" effect of an exposure on disease occurrence is not a biological constant; it is modified by spatial scale.

Relationship between Spatial Scale and Disease Clustering

Issues of spatial scale and resolution affect virtually all statistical analyses of exposure, health effects and the exposure-effect link. For purposes of illustration, consider an investigation of the pattern of disease incidence in areas where the population is suspected of being exposed to a hazardous environmental agent (to

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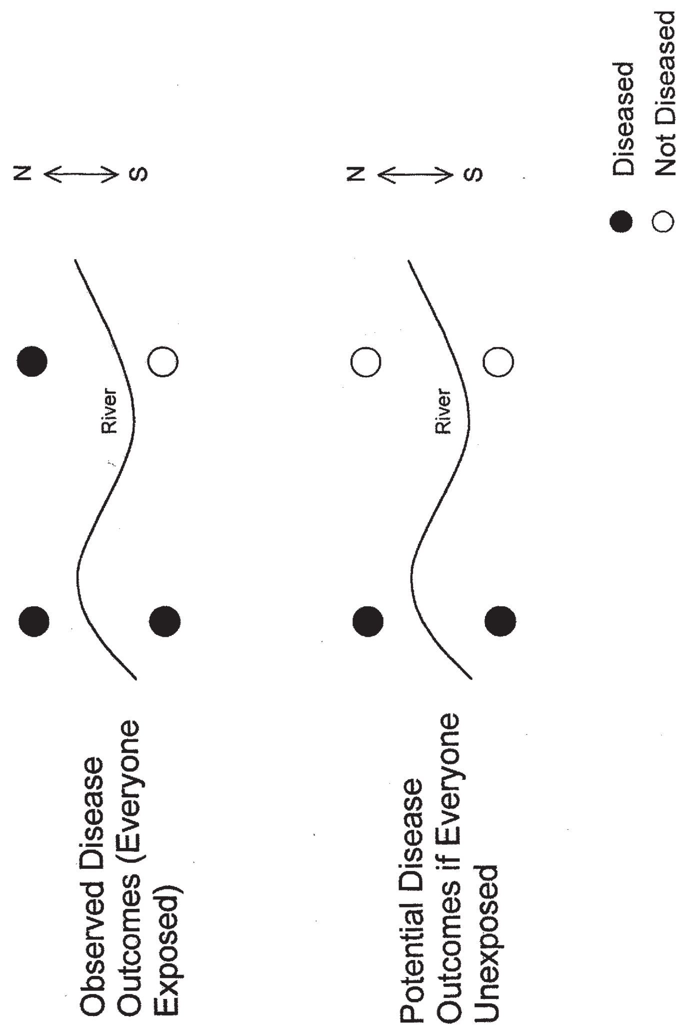

Figure 3. **Comparison of observed and potential disease outcomes for a hypothetical town during a given observation period under two different exposure scenarios.**

which others are not exposed). In such studies the analyst typically assigns a location to each person who has the disease (commonly his or her residence) and then uses statistical techniques to look for spatial patterns of disease cases that might suggest a higher incidence in areas of putative exposure. Detecting a "disease cluster" in an area where people are likely to be exposed suggests the possibility that the "cluster" is an environmentally induced effect.

The idea of disease clustering is relatively easy to grasp, but its application to environmental health studies is complicated by spatial issues. Besides the fact that magnitude, duration and frequency of environmental exposures are related to spatial scale, the concept of clustering is itself scale dependent. As shown in Figure 4, even though the number and relative position of disease cases stays the same, they can appear random at one scale and clustered at another.

For example, public concern about possible "cancer clusters" is sometimes reported in the media. Typically, a family, a group of friends, a neighborhood or a community will become convinced, based on anecdotal evidence, that they are experiencing a higher than average incidence of cancer. However, when cancer incidence is examined rigorously using appropriately scaled and resolved data, most of these "clusters" disappear. Often there is no way, *a priori*, to tell which spatial scale is most appropriate for the environmental health issue being investigated.

Complications can also arise when disease incidence data are aggregated into cases per subregions of the larger study area because of concerns about protecting confidentiality. For example, instead of having individual data points (like those portrayed in Figure 4) for an entire city, it is common to have only number of cases per block-group or tract. Because the number of cases is reported only by subregion, any clustering at a spatial scale smaller than the subregion will be impossible to detect. Moreover, aggregation of case locations into subregional counts can split small clusters that occur near boundaries between neighboring subregions, thereby reducing their likelihood of detection.

Effects of Spatial Scale and Resolution on Census Data

The effects of spatial scale and resolution on census data are illustrated in Figure 5. Figures 5a and 5c show the City of Minneapolis, while Figures 5b and 5d show Hennepin county (the county in which Minneapolis is located). Figures 5a and 5b depict spatial resolution at the census block group (average block group contains about 1000 people) and Figures 5c and 5d depict spatial resolution at the census tract (average census tract contains about 4000 people). Although census tract has historically been the standard unit for urban-based analyses, studies using block-group level analysis have increased rapidly during the 1990s due to the creation of easily obtainable digital block-group boundary files. The differences shown in Figure 5 raise a basic question: what is the optimal scale and resolution for a given study? Or perhaps more appropriately, is there an optimal scale and resolution?

These questions are difficult to answer because relatively little is known about the variance of the data within a particular enumeration unit (block, block group, tract). Although enumeration units are often treated as logical, cohesive, and homogeneous units of analysis, the reality is that they are virtually meaningless in many cases because data tend to be spatially continuous rather than discrete. It is

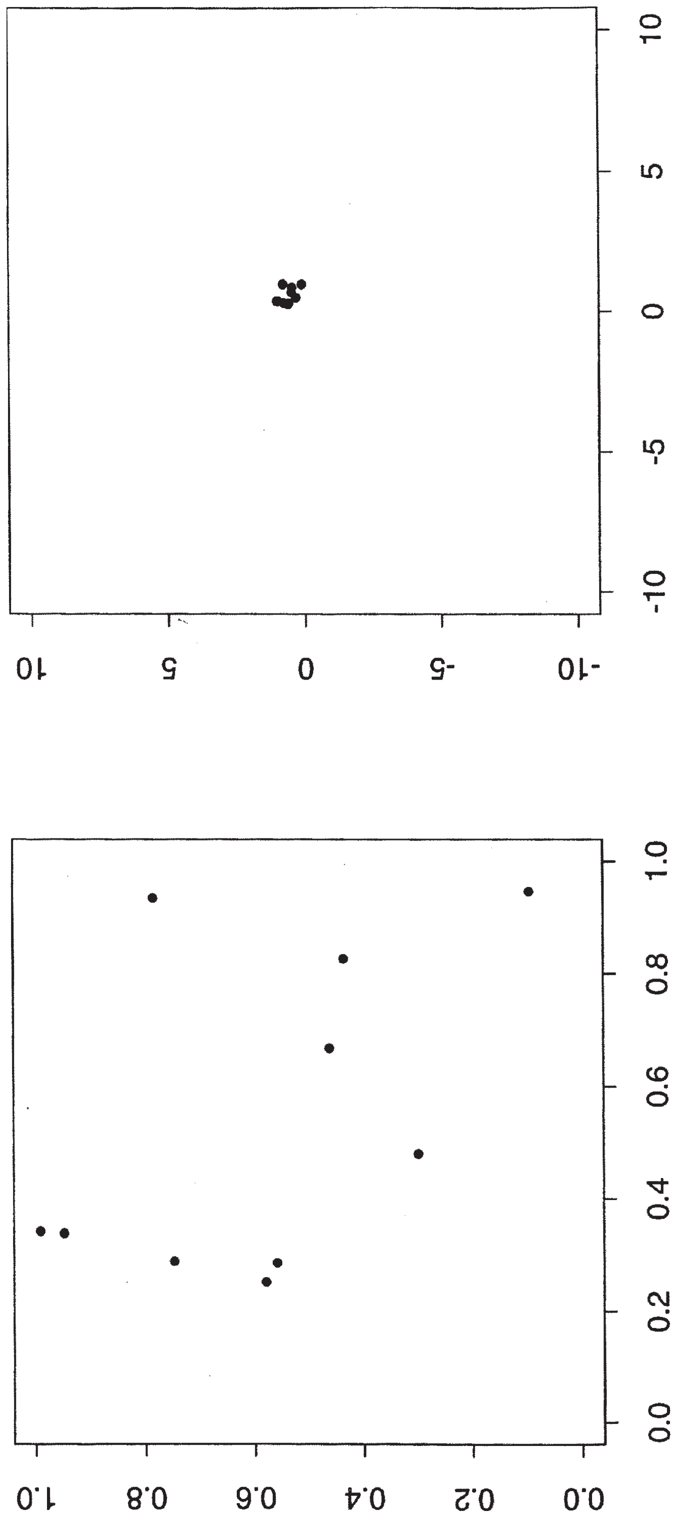

Figure 4. The implications of spatial scale for disease clustering — the same number and relative positioning of disease cases can appear random at one spatial scale and clustered at another.

Figure 5. An illustration of the effects of spatial scale and resolution on census data: (A) City of Minneapolis resolved by block group; (B) Hennepin County resolved by block group; (C) City of Minneapolis resolved by tract; (D) Hennepin County resolved by tract (on average a block group contains 1000 people and a tract contains 4000 people).

not unusual, for instance, for the variance of an environmental health variable to be greater within than between enumeration units, which argues for using the finest resolution possible.

One area where spatial issues are especially important is the study of "environmental justice" — the contention that poor communities and people of color bear a disproportionate burden of environmental hazards (Sexton 1997). Recently, McMaster *et al.* (1997) demonstrated that results of environmental justice studies, which used data from the Toxics Release Inventory (TRI) in the Minneapolis-St. Paul metropolitan area, depended on both spatial scale and resolution (block, block-level, tract). Thus, findings of environmental health disparities between population groups were found to be sensitive both to the enumeration unit (scale) and the level of aggregation of the data (resolution).

Harking back to our earlier discussion of the MAUP, it should come as no surprise that results of statistical analyses to (a) infer causality, (b) identify and elucidate disease clusters and (c) characterize issues of environmental justice can change significantly with spatial scale and resolution (Openshaw 1984). As several investigators have observed, the potential significance of spatial scale and resolution for statistical data analysis means that any positive finding linking environmental exposure with location of disease cases suggests a possible statistical association *only* at the same spatial resolution as the data (Cleek 1979; Waller and Turnbull 1993). Or in other words, the resolution of the data for exposure and health effects limits the spatial scale of detectable statistical association, thereby providing a context within which results must necessarily be interpreted.

IMPORTANCE OF SPATIAL SCALE FOR ENVIRONMENTAL HEALTH

Spatial scale and resolution are an integral component of activities directed at protecting and enhancing environmental health. They have ramifications for the design and interpretation of studies aimed at increasing knowledge and furthering understanding about the three fundamental variables in environmental health: exposure; health effects; and the exposure-effect link. Spatial scale and resolution are also crucial for the formulation, implementation, and evaluation of public policies intended to prevent or reduce exposures and related health effects. In order to appreciate fully the crucial role played by spatial issues, it is necessary to comprehend the nature of the relationship between research and policy in the context of safeguarding environmental health.

A simplified diagram of the connection between research and policy is provided in Figure 6. In the field of environmental health, the overarching goal is to understand the "truth" about exposures, health effects, and the exposure-effect link so that this information can be used to improve quality of life (environmental health) for as many people as possible. Based on the traditional public health model, the highest priority goal for improving quality of life is primary prevention, which entails anticipating and preventing adverse health outcomes before they occur. Secondary prevention is the next highest goal, and it involves intervening to stop or limit effects (exposures) when primary prevention fails. Tertiary prevention (treatment) is the last resort, requiring that health care professionals treat the impairments and disabilities of affected (exposed) individuals.

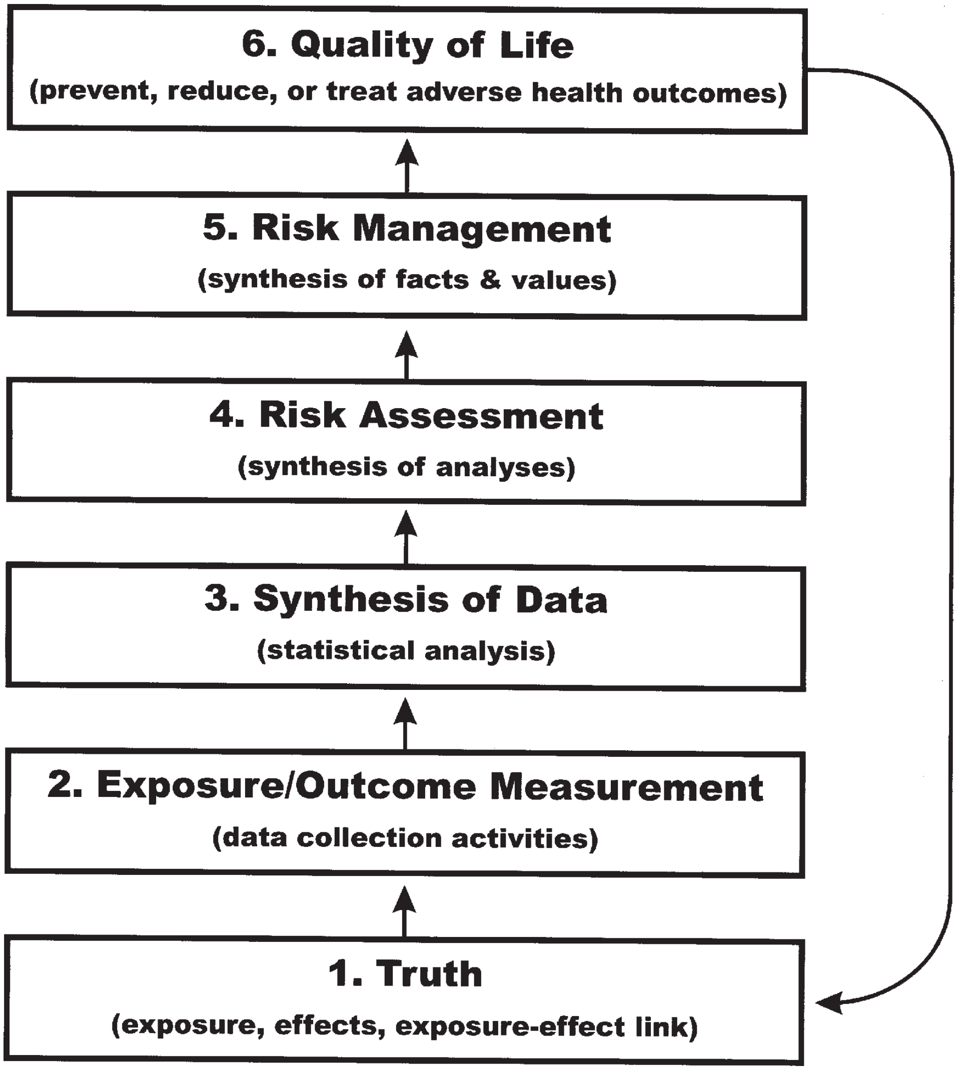

Figure 6. Simplified flow diagram of key events and activities in environmental health.

As shown in Figure 6, the general flow of information in environmental health is from studies that measure exposure or health outcome (collection of data to estimate the "truth"), to synthesis or integration of the data (statistical analysis), to assessment of health risks for exposed individuals and populations (synthesis of statistical analyses), to decisions about the acceptability/unacceptability of health risks and what, if anything, to do about those deemed unacceptable (synthesis of facts and values). The diagram also depicts the fact that implementation of environmental health policies, whether they are successful in achieving their stated objectives or not, can affect the "truth" (*e.g.*, geographical distribution) for exposures, health effects, and the exposure-effect link.

To illustrate the importance of spatial scale and resolution at each stage in Figure 6 consider a simple example. Assume that a single chemical is emitted into the air from a lone point source located in the midst of a town, that all exposures to residents occur via inhalation, and that airborne levels of the chemical are due solely to the individual point source (*i.e.*, background concentration is zero). Further assume that long-term, low-level exposures to the chemical may cause a chronic effect (*e.g.*, liver cancer) in some individuals, while short-term, high-level exposures may cause an acute effect (*e.g.*, inflammation of upper airways) in some individuals. We assume that neither outcome is certain with exposure (assume differing susceptibilities) but that the risk of each outcome generally increases with increasing exposure. Highest exposures are assumed to occur near the point source and to gradually decrease with increasing distance. Finally, the high-exposure outcome is assumed to occur only at exposures above a certain threshold, while no threshold is assumed for the low-dose outcome.

The true exposure-effect relationship (*i.e.*, "truth" in Figure 6) depends on which health outcome is considered. Since highest exposures occur near the emission source, the high- exposure effect will be limited to a relatively smaller geographical area in somewhat closer proximity to the source than the low-exposure effect. Consequently, spatial scale and resolution are critically important for efforts to estimate the true association between environmental exposure and related health outcomes with a reasonable degree of accuracy and precision.

In terms of studies designed to measure true underlying relationships, spatial resolution of exposure monitoring data and health outcome data will affect results. Validity of interpolation methods and size of measurement errors will affect exposure estimates, while health outcome data may be aggregated at the level of census districts, which will define scale, resolution, and boundary issues for exposure-outcome analyses. Incompatibility between the scale of true disease processes and the resolution of exposure and health outcome data can compromise results of statistical analyses. The use of aggregated observational data increases the potential for interpretations that succumb to the ecological fallacy (inferring individual causality from population-based data), and choices of boundaries and resolution limit the observable effects that can realistically be detected.

For purposes of assessing health risk, assessors often must combine multiple exposure or epidemiologic studies, each focusing on a different spatial scale with different spatial resolution. Individual studies may be independently accurate, therefore, but appear to be contradictory without proper consideration of the diversity of spatial scales and resolution employed. For example, suppose that airborne emissions from a particular source are not sufficient to reach the threshold exposure for the high-exposure outcome. A study of the high-exposure health outcome around this specific source would correctly find no association between exposure and the acute effect, while studies around similar sources (but with higher exposures) in other towns might correctly find a strong statistical association.

Risk management involves the use of risk assessment results, in combination with consideration of social, economic, legal, political and ethical issues, to decide which health risks are unacceptable and what to do about them. Spatial scale and resolution, as well as choices of spatial boundaries, are important in relation to defining the geographical scale for implementation and evaluation of environmental health policies. For instance, a policy decision might be made to manage the high-exposure risks by requiring exposure monitoring at some specified distance from the emission source and mandating that measured exposures not exceed the threshold for acute effects (subject to monetary penalties). This policy entails a decision about the appropriate spatial distance from the source for exposure monitoring, and implies protection for people living beyond the monitors but not necessarily for those living or working closer to the source.

The results of this policy, whether stated objectives are attained or not, have the potential to affect the "truth" (*e.g.*, geographical distribution of exposures and health outcomes). In our example, the policy decision to limit exposures at a certain distance from the source is likely, over time, to modify the true spatial scale of exposures to the chemical, which will affect the appropriate spatial scale and resolution for well-designed epidemiologic studies. The point is that changes in the true underlying distributions of exposure, health outcomes, and exposure-effect link are possible and have ramifications for the entire process summarized in Figure 6.

CONCLUSIONS

Issues of spatial scale and resolution are fundamentally important to the field of environmental health for two reasons. First, the true geographical distributions of exposure, health effects, and exposure-effect link are dependent on spatial scale and, second, results of statistical analyses (for data on exposure, health effects, and exposure-effect link) are dependent on spatial scale and resolution. Consequently, decisions about environmental health policy and research must necessarily occur within the context of spatial scale and resolution. We believe this context should be made more explicit, thereby forcing policy makers and researchers to confront three key questions.

- What is the appropriate spatial scale for implementing policies to protect environmental health or for collecting and analyzing environmental health data?

- For the spatial scale of interest, and for the particular exposures and health outcomes under consideration, what is the actual (true) geographic distribution of exposure, health effects, and exposure-effect relationship?

- What are the effects of spatial scale and resolution on results of statistical analyses and how should this affect interpretation of results?

Answering these questions realistically is becoming more critical as increasingly greater reliance is placed on GIS as a decision-making tool. The promise of GIS to improve environmental health studies, make risk assessments more realistic, and inform environmental health policies cannot be fully realized unless and until we develop a better understanding of crucial spatial issues.

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